Modeling Phosphorus Dynamics of Tonle Sap Lake

Veasna Kum*1, William C. Burnett2

1Department of Civil Engineering, Zaman University, Phnom Penh, Cambodia

2Department of Earth, Ocean & Atmospheric Sciences, Florida State University, Tallahassee, FL, 32306, USA

*1kveasna@zamanuniversity.edu.kh; 2wburnett@fsu.edu

Abstract

Concerns have recently been expressed that development, such as dam construction, in the Mekong River Basin will affect the flow of the river and the nutrient flow to the Tonle Sap (TS) Lake in Cambodia. This paper presents a dynamic phosphorus (P) model that was built to investigate the response of the lake's phosphorus cycle to changes in P loads under different development scenarios for the Mekong Basin including a high development (HD) scenario as well as current conditions. Understanding the P cycle is important as it is considered the limiting nutrient for organic productivity of the lake. The dynamic characteristics of the lake and the deficiency of data require a careful design of the P model structure. We developed a simple phosphorus budget model demonstrate here its application to the TS Lake. The P model was based on System Dynamics (SD) methodology and the model was constructed in Vensim, a software for building dynamic models. Results showed that the P peak concentration of the lake under the HD scenario would be lower than that under the baseline scenario by about 30%. However, the basic cyclic behavior of P of the Lake under the two scenarios did not change significantly. Both actual data and the model output indicates two peaks per year in the P concentrations in the lake, likely a reflection of different sources during different stages of the annual flood/withdrawal cycle.

Keywords

System Dynamics Modeling; Vensim; Phosphorus; Tonle Sap; Mekong River; Cambodia

Introduction

The TS Lake in Cambodia (Figure 1) is the largest freshwater lake in Southeast Asia. The Lake is very rich in biodiversity and is considered the "Heart and Soul" of the Cambodian people. The lake is believed to be among the world's most productive freshwater ecosystems and the importance of the lake is well documented in the literature. The lake nourishes a community far larger than the 2.9 million Cambodians who live around it (Gill, 2003). It covers an area of approximately 250,000 ha during the dry season. However, during the wet monsoon season from May to October, the lake expands tremendously (Hand, 2003) with its area increasing about five-fold. This results in some 1.25 million ha of forest and agricultural land being submerged beneath as much as 10 m of water for a period of several months each year (Lane and Neou, 2002). This unique hydrological cycle creates a rich biodiversity of fish, reptiles, birds, and mammals. The lake also serves as a giant nursery for the Mekong River. Fish spawned in the lake's flooded forests and vegetation during the wet monsoon migrate to the Mekong River in the dry season, traveling upstream possibly as far as the People's Republic of China, as well as downstream to the Mekong Delta (Lane and Neou, 2002).

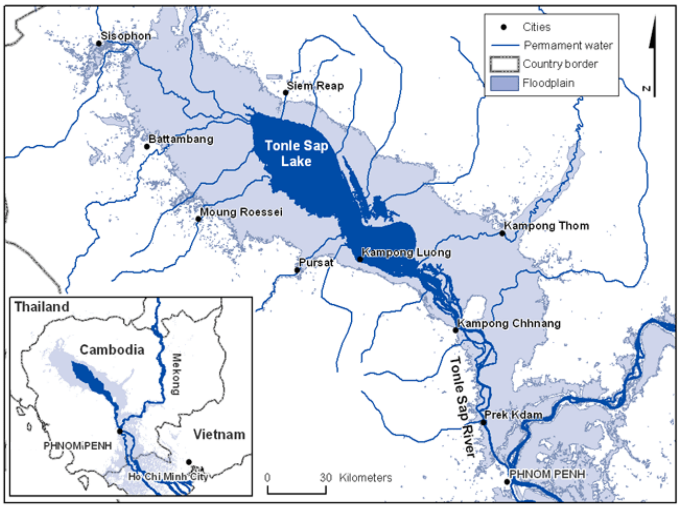

FIG. 1 MAP OF TS AND ITS FLOODPLAIN

The TS Lake is an integral part of the Mekong River. It serves to balance the annual floods from the Mekong River, one of the world's longest waterways that threads through six countries of the Greater Mekong Sub-region, including Cambodia, People's Republic of China, Lao People's Democratic Republic, Myanmar, Thailand and Vietnam. The lake is believed to be among the world's most productive freshwater ecosystems and the importance of the lake for Cambodia is well documented (Rainboth, 1996; Neou,

2001; Kite, 2001; Campbell et al., 2006; Keskinen, 2006; Keskinen et al., 2007; Kummu and Sarkkula, 2008 and Lamberts, 2008).

The TS Lake is very shallow in the dry season with an average depth ~0.5 m, exceeding 3 m in depth in only a few locations. The mean depth at the height of the flood is about 7 m. The changing water level has a number of consequences for the lake's chemistry and ecology. As the water level decreases during the dry season, turbidity increases, presumably because sediment from the lakebed is re-suspended as a result of wind-generated turbulence (Campbell et al., 2009).The lake is very rich in biodiversity, which many researchers believe is largely due to the annual flooding (Keskinen et al., 2007; Kummu and Sarkkula, 2008; Lamberts, 2008; and (Lamberts, 2006). The annual flooding of the lake will likely be directly impacted by the construction of the proposed large hydropower dams and reservoirs in the middle and lower reaches of the Mekong River because around 60% of the TS floodwater originates from the river (Kummu and Sarkkula, 2008). Recently, concerns that development, such as dam construction, in the Mekong River Basin will affect the flow of the river and the nutrient flow to the TS ecosystem have increased (Kummu and Sarkkula, 2008; Lamberts, 2008; and Kummu et al., 2005).

Reference (Kummu and Sarkkula, 2008) compiled a cumulative impact assessment of the construction for large-scale hydropower dams and reservoirs in the upper part of the Lower Mekong Basin. They based their assessment of the impact on the flow to TS Lake by reviewing reports of the Mekong River Commission (MRC) and the Asian Development Bank (ADB). The authors predicted that over a 20-year time frame with a high development scenario, the maximum water level of the lake will be lowered by 0.36 to 0.54 m and the minimum water level of the lake would increase by as much as 0.6 m (Kummu and Sarkkula, 2008). Many scientists have warned that the valuable biodiversity and natural capital of the TS Lake is susceptible to degradation when the floods that drive its productivity are altered (Kite, 2001; Keskinen et al., 2007; Kummu and Sarkkula, 2008; Lamberts and Koponen, 2008; Sarkkula et al., 2009; and Sarkkula et al., 2009). We will use a baseline scenario (BAU, "business as usual") for the current situation while the high development (HD) scenario assumes that the maximum water level of the lake would be lowered by 0.36 to 0.54 m and the minimum water level of the lake would increase by as much as 0.6 m. More detailed descriptions about the scenarios can be found in (Kummu and Sarkkula, 2008).

The TS Lake and floodplain ecosystem is a complex ecosystem which is poorly understood (Lamberts, 2008). Many interrelationships between components in the system exist and these components change over time. This complexity, together with data deficiencies, leads many researchers to conclude that highly predictive models cannot be constructed. Thus, we need a modeling methodology which is less dependent on quantitative data.

SD modeling predicts future states by showing feedback mechanisms among the system components rather than forecasting future states using time series data (Choi, 1997). Thus, SD modeling is less dependent on the accurate estimation of parameters. The features of SD and the way an SD model is conceptualized make this methodology particularly appropriate for this research because time series data for many variables needed for such an analysis do not exist.

It is very likely that dam construction in the Mekong River Basin will affect the nutrient flow to the TS ecosystem. Becasue P is the limiting nutrient in the lake (Sarkkula et al., 2004), the river flow's effect on the dynamics of the lake's P cycle needs to be understood. The goal of this paper is to evaluate the behavior and dynamics of total phosphorus (TP) in the lake under both the baseline (BAU) and the high development (HD) scenarios.

Some Existing P Models

Numerous attempts have been made to model P concentration in lakes (Seo and Canale, 1996). However, the design and complexity of the models developed for P differ greatly. Some models are empirical and others are based on mass balance principles. Some models consider P concentration alone, while others partition total phosphorus into dissolved and particulate components. Some models assume that the water column is completely mixed, while others may divide it into two or more layers. Many models are concerned only with the water column whereas others may consider explicit interactions between water and sediments. The phosphorus models reviewed here represent a few examples that range from extremely simple to very complex. Each model has advantages and disadvantages, which should be carefully considered prior to a specific application.

One of the main dilemmas in building dynamic models of environmental or ecological systems is the level of detail and complexity. Reference (Seo and Canale, 1996) evaluated eight P models of varying degrees of complexity, including models with routines for sediment exchange and division of P into dissolved and particulate fractions. Their results indicated that allowing for seasonal variation of diffusion from sediments and sedimentation is crucial for successful modeling. However, while introducing new processes or compartments may increase the predictive power to some degree, the number of unknown parameters will also increase, as well as the total model uncertainty (Malmaeus and Håkanson, 2004). Although simple models may have limited predictive value, complex models are difficult to apply and may actually increase the uncertainties of model predictions (Beck, 1981) and (Wang et al., 2003)). On the other hand, complex models are not necessarily better than simple ones (Jørgensen, 1982). Thus, the chosen level of complexity is largely dependent on the purpose of the model. Omitting or over-simplifying an important process necessarily creates a need for compensation somewhere else in the model.

Various researchers have examined the nutrient balance using a one-box model for lakes. Reference (Vollenweider, 1969) showed that in an advanced form, a model could lead to an equation connecting mean nutrient connections to a few relevant lake parameters. That model was designed as a simple eutrophication model, which assumed complete mixing and accounts for input and output to the lake with a net loss of phosphorus to the lake sediment. Reference (Vollenweider, 1974) later showed that if the rate of natural and man-made phosphorus inputs to lakes and the sedimentation rates are known, then the system response to phosphorus loadings can be estimated. These models were developed using data from predominately deep temperate lakes and so the impacts of internal phosphorus cycling and the expedited metabolic rate characteristic of shallow, tropical/subtropical lakes were not considered. Although these models have been proven successful in some lakes, they often fail to predict lake phosphorus concentrations in other lakes. Unfortunately, understanding when they work and when they do not is not a trivial matter (Malmaeus and Håkanson, 2004).

Reference (Dillon and Rigler, 1974) modified the model in (Vollenweider, 1969) by calculating a phosphorus retention coefficient from all known inputs and outflows in order to eliminate the need to measure the sedimentation rate. This model only considers steady-state conditions, however, and thus cannot be used to study seasonal variations, which clearly are very important in the TS system.

A dynamic model of sediment-water interactions, with particulate-P and pore water P in sediments considered to be a direct source for phosphorus release was presented in (Lorenzen et al., 1976; Chapra and Canale, 1991). Chapra and Canale (1991) considered sediment release of phosphorus assuming that the release of phosphorus is a function of the sediment P content, dissolved oxygen and temperature at the lake bottom. The sediment system is coupled with the lake system by releasing sediment nutrients as nutrient input to the water from other sources decreases. In recent decades, researchers used mass transport and balance considerations within the sediments to study phosphorus distribution profiles and consequently release fluxes (Van Eck and Smits, 1986; Boers and Hese, 1988; Ishikawa and Nishimura, 1989). The method also includes more detailed processes such as phosphorus regeneration rates from organic matter decomposition. Release of phosphorus from sediments, however, is a process that varies both temporally and spatially. Most developed models have resulted in a constant flux of phosphorus under steady-state conditions, which limits the application of these models for the dynamic predictions needed for the TS situation. The steady-state approach delivers realistic results for equilibrated systems, but has proved impractical for predicting results needed for lake management applications.

A more sophisticated phosphorus model of the sediment-water interface with detailed mechanisms can be found in (Smits and van der Molen, 1993). The model describes the dynamic exchange of nutrients between sediments and the overlying water by dividing the shallow portion below the water-sediment interface into four sub-layers. However, a major disadvantage of this model as noted in (Wang et al., 2003) is that a detailed division of sediment layers may complicate the model without proportionally improving its performance. Moreover, most of model parameters cannot be estimated experimentally. Reference (Wang et al., 2003) also wrote that the interaction between sediments and the overlying water occurs is generally thought to be mainly in the uppermost active layer of ~10 cm or less.

Some argued that in shallow lakes extensive exchange occurs between phosphorus in the water column and phosphorus in the sediments, while a substantial part

of the relevant available phosphorus pool in such lakes is present in the sediment rather than the water column (Scheffer, 2004). In general, a number of processes are involved with the transformation of phosphorus between the particulate and the dissolved forms. The typical processes include oxidation and breakdown of organic material, oxidation and reduction of associated inorganic species (e.g., Fe, Mn), physio-chemical adsorption, precipitation and solution of phosphorus to and from mineral forms. For most of these processes, complete theories and detailed descriptions including the kinetics of the reactions are still lacking. Thus, we consider a simpler representation of phosphorus dynamics in sediments as modeled in (Lorenzen et al., 1976). The approach in (Lorenzen et al., 1976) was thought to reasonably reflect the effects of phosphorus retention and the importance of phosphorus release from sediments, especially in shallow lakes (Ruley and Rusch, 2004).

Methods

Monsoon floods from the Mekong River drive the hydrology of TS Lake. The main portion of the in-flow to TS Lake is coming from the Mekong River directly through the TS River that connects the lake to the Mekong. However, relatively small tributaries and over-land flow through the floodplain also contribute to the wet season water inflows.

Phosphorus dynamics in the lake is dependent on the inflow and outflow of phosphorus and the loss and release to/from the sediments. Figure 2 shows a conceptual model that illustrates the principal inputs and outputs of P that are considered in our model. For the present case, the form of phosphorus being considered is total phosphorus (TP), which includes particulate and dissolved forms of P. In addition, we have neglected groundwater inflows for this model. Although potentially important (Burnett et al., 2012), the data do not currently exist to model the P inputs via groundwater.

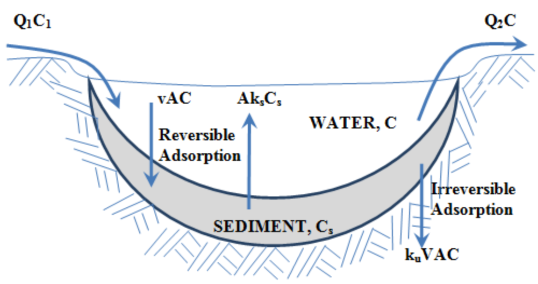

FIG. 2 DIAGRAMATIC REPRESENTATION OF P DYNAMICS IN TS LAKE

To understand the dynamics of P in Tonle Sap, a dynamic model based on ordinary differential equations was developed and calibrated by comparison to a one-year time series of water quality data. A mass balance of both sediment and P concentrations yields the following coupled differential equations. The explanation of these parameters and coefficients is given in Table 1.

$$\frac{dCV}{dt} = Q_1C_1 - Q_2C - vAC + k_sAC_s \quad (1)$$

$$\frac{dC_sV_s}{dt} = vAC(1-k_u) - k_sAC_s \quad (2)$$

Eq. 1 states that the rate of change of P mass in the water column is equal to the input rate from water inflow minus the loss rate from water outflow minus the deposition rate to sediment plus the regeneration from sediments. Eq. 2 states that rate of change of P in a surface sediment layer is equal to the input due to sediment deposition from the water column minus the rate at which P becomes permanently buried in the sediment minus the loss due to regeneration into water column. Both Eq. 1 and Eq. 2 are written to show that both the P concentration and the volume of the lake (V) change over time, a critical factor in the case of TS Lake. Some authors setup mass balance equations with the notation in the form of VdC/dt rather than dCV/dt. These two terms would be equal only when V is constant.

TABLE 1 NOTATION IN TP MODEL EQUATIONS

Symbols	Description	Unit
Q_1	Inflow rate of water to the Lake	L/month
Q_2	Outflow rate of water from the Lake	L/month
C_1	TP concentration in inflow	mgP/L
C	TP concentration in the Lake	mgP/L
v	Apparent settling rate of particulate-P	m/month
A	Surface area of the Lake	m^2
C_s	Particulate-P concentration in sediment	mgP/L
k_s	Release rate of phosphorus from sediment	m/month
k_u	Non exchangeable fraction of TP input to sediment	dmnl
V	Volume of water in the Lake	L
V_s	Volume of the sediment in active layer	L

dmnl = dimensionless

Some concern exists about the quantity of sediment entering TS Lake because some areas in the lake have

become shallower and are now scarcely navigable in the dry season. However, the precise rate at which sediment is accumulating in the lake is not well known, and estimates vary dramatically. Some proposed a sedimentation rate of 0.3 mm/year (Carbonnel and Guiscarfe, 1965). However, a sediment accumulation rate as high as 40 mm/year was also reported (Gartrell, 1997). Reference (Sluiter, 1993), without any form of substantiation, stated "in the 1960's the bottom of the lake was rising two centimeters every year, and by 1990 this rate had increased to four centimeters per year." Table 2 compiles previous estimates of the sedimentation rate of TS Lake. In a more recent study, the average sedimentation rates between dated horizons within four cores ranged between 0.05 and 2.55 mm/year with a long-term average of 0.66 mm/year across the lake basin (Kummu et al., 2008). Kummu et al. (2008) also pointed out that some of the claims about sedimentation rate in the literature are dubious or based on a misinterpretation of exploratory work, which have proved inconclusive and misleading. The authors calculated an average sedimentation rate of 0.27 mm/year assuming that sediment supplied by the Mekong River via the TS River settled out evenly over the entire lake including the floodplain area. However, it is known that sediment does not settle out evenly but is trapped by vegetation within the floodplain. Because the sedimentation rate in the lake is likely not so high, the volume of the sediment (V_s) in this paper is assumed constant over the time course of simulation (a few years).

TABLE 2 SEDIMENTATION RATES REPORTED FOR TONLE SAP LAKE

Value	**Unit**	**Source**
0.3	mm/year	[38]
40	mm/year	[39]
20-40	mm/year	[40]
0.05-2.55	mm/year	[41]

The contact area between water and sediment is reasonably assumed to be equal to the lake area because the lake has a relatively flat bottom (Campbell et al., 2009) and the slope of the TS banks is very high. The high-slope assumption is based on the data provided by Dr. Matti Kummu (Pers. Comm.) showing that as the lake area increases ~6 times (2.38 x 10^9 m^2 to 14.4 x 10^9 m^2) from the dry to the flood stage, the volume increases ~40 times (1.79 x 10^9 m^3 to 68.9 x 10^9 m^3) over the same period. The water level measured and the corresponding surface area and volume of the lake calculated over this one-year period are presented in Table 3. The P concentrations in TS lake were sampled at Kompong Luong, KGL (N: 12.66° and E: 104.23°) and the P concentration in the TS river was sampled at Kompong Chhnang, KCH (N: 12.26° and E: 104.68°), located just at the mouth of the lake (FIG. 1). The recorded values are presented in Table 4.

TABLE 3 SEASONAL WATER LEVEL, AREA AND VOLUME OF TS LAKE

Month	Water Level (WL) (m)	Lake Area (LA) (m2)	Lake Volume (LV) (l)
Apr-01	1.46	2.38E+09	1.79E+12
May-01	1.73	2.70E+09	2.34E+12
Jun-01	3.79	5.30E+09	1.00E+13
Jul-01	6.56	9.19E+09	3.01E+13
Aug-01	8.79	1.27E+10	5.45E+13
Sep-01	9.87	1.44E+10	6.89E+13
Oct-01	9.38	1.36E+10	6.22E+13
Nov-01	8.29	1.19E+10	4.84E+13
Dec-01	6.12	8.54E+09	2.62E+13
Jan-02	4.41	6.13E+09	1.35E+13
Feb-02	2.98	4.24E+09	6.26E+12
Mar-02	1.98	3.00E+09	2.94E+12

Source: Data provided by Matti Kummu (pers. comm.)

TABLE 4 SEASONAL CONCENTRATION LEVEL OF TP IN TSL AND TSR

Month	TP at TSR (mgP/L)	TP at TSL (mgP/L)
Apr-01	0.070	n.a
May-01	0.060	n.a
Jun-01	0.061	0.061
Jul-01	0.017	0.016
Aug-01	0.011	0.014
Sep-01	0.010	0.009
Oct-01	0.008	0.005
Nov-01	0.012	0.007
Dec-01	0.009	0.019
Jan-02	0.018	0.012
Feb-02	0.019	0.024
Mar-02	0.027	0.013

Source: Data provided by Matti Kummu (pers. comm.)
Note: TSL: Tonle Sap Lake, TSR: Tonle Sap River

As mentioned earlier, under the HD scenario, the maximum water level of the lake would be lowered by 0.36 to 0.54 m and the minimum water level would increase by as much as 0.6 m. Data for water level, lake area and volume were plotted and functions representing water level (F_1), area (F_2) and the volume (F_3) are presented below:

$$F_1 = f_1 Sin\left[\frac{2\pi}{w}(t - f_3)\right] + f_2 \tag{3}$$

$$F_2 = f_4 * F_1 \tag{4}$$

$$F_3 = f_5 * F_1^2 \tag{5}$$

Where t is time, w is the water period and f_1, f_2, f_3, f_4 and f_5 are all fitting constants (Table 5). Figure 3 displays the model fits to the observed data.

TABLE 5 CONSTANT VALUES OF THE FITTING FUNCTIONS

Fitting constants	value	unit
f_1	4.177	m
f_2	5.457	m
f_3	2.552	month
f_4	1.44e+009	m
f_5	7.11e+008	m
w	12	month

The P model was built in Vensim, a software program that facilitates one to conceptualize, document, simulate, analyze and optimize models of dynamic systems (Ventanna, 2012). The model was run for a period of six years with a one month time step. Longer runs, out to 10 years, showed that there was no further change in the TP concentration patterns. Three parameters: v, the particle settling rate; k_s, the phosphorus regeneration rate and k_u, the P burial fraction in Eq. 1 and Eq. 2 used in the model have not been measured for TS Lake. These parameters are very difficult to be measured because of the contraction-expansion characteristics of TS Lake.

Table 6 presents a range of values for these parameters found in the literature (Lorenzen et al., 1976; Chapra and Canale, 1991; Imboden, 1974; Snodgrass and O'Melia, 1975; Chapra, 1997). These values are used as inputs to calibrate the parameters to obtain a good fit to the actually measured P concentration in the lake.

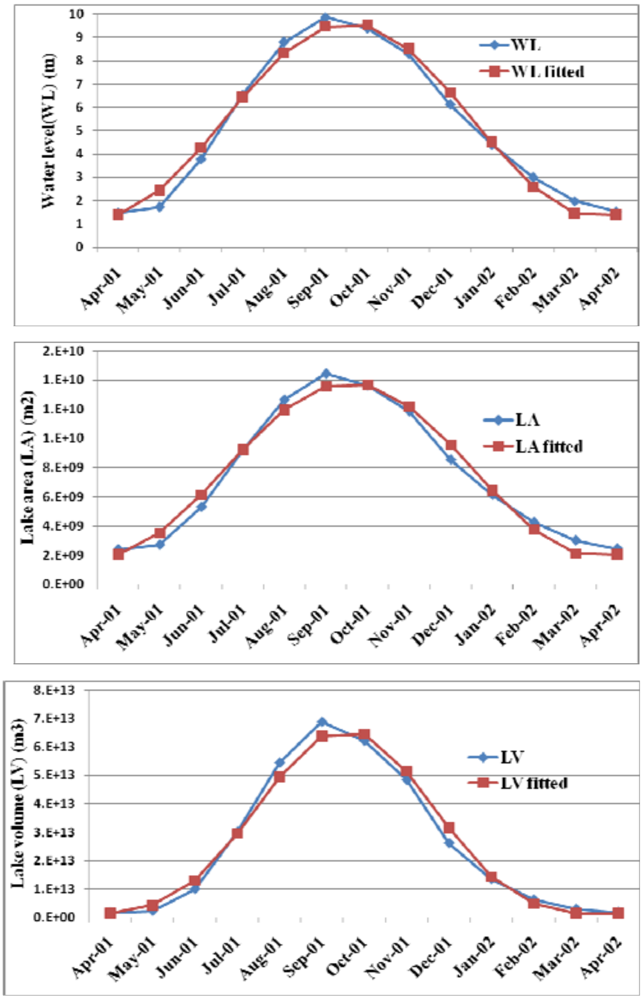

FIG. 3 CURVE FITTING TO THE DATA ON WATER LEVEL (WL), LAKE AREA (LA) AND VOLUME OF TS LAKE (LV)

TABLE 6 RANGE OF VALUES OF V, K_S AND K_U

Parameter	Value	Unit	Source
v	3-12	m/month	[36]
	3-8	m/month	[37]
	0.42-1.67	m/month	[38]
k_s	0.001	m/month	[29]
	0.00041-0.0009	m/month	[26]
k_u	0.6	dmnl	[29]

Simulation Results

After the calibration runs, P as generated by the model best fits the historical data when v =1 m/month, k_s = 0.0009 m/month and k_u =0.3. The k_u value is lower than the 0.6 value reported by (Lorenzen et al., 1976) for Lake Washington. According to studies concerning P release from sediment in shallow lakes in the middle

and lower reaches of the Yangtze River area in China, over 80% of P in the sediment in these shallow lakes is released easily (Wang et al., 2006). This means that the burial fraction of P in shallow lakes may not be very high and thus the k_u value calibrated by our model seems reasonable. These calibrated values are assumed to be constant while performing the test of the impact of changing flood magnitude on the dynamics of P in the lake. Flood magnitude here is referred to the highest water level of the lake during the flood season. Two cases are considered here: one is the behavior of P under a completely deterministic frame work (no variation of flood magnitude) and the other one is the behavior of P under a stochastic variation of flood magnitude.

Deterministic Case

In one case, we make the assumption that there is no variation of the flood magnitude or pattern over the time course of simulation and the annual flood magnitude is the same as the sample year of 2001/2002. Figure 4 shows the predictions of the model under these assumptions together with actual P measurements for comparison.

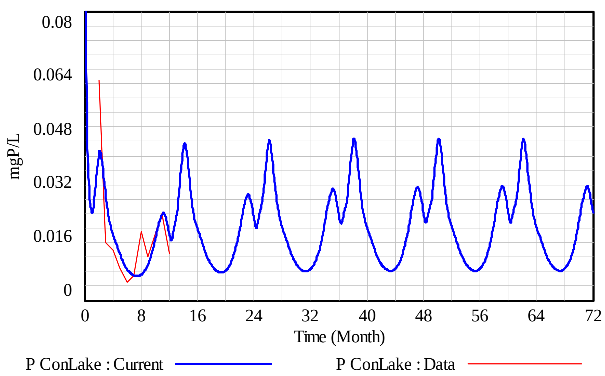

FIG. 4 BEHAVIOR (UNDER DETERMINISTIC CASE) OF THE TP UNDER CURRENT CONDITIONS, A "BUSINESS AS USUAL" (BAU) SCENARIO

The starting point (0 on x-axis) in FIG. 4 is April 2001.The dual TP peaks that occur each year in about mid-March (near end of dry season) and July (wet season) may be in response to different sources of TP during different hydrologic conditions.

In the next case, we investigate the behavior of P under a HD scenario. Under the HD scenario in the Mekong Basin, reference (Kummu and Sarkkula, 2008) reported the maximum water level in the lake would decrease from 0.3m to 0.6m. An average value (0.45 m) is used for this deterministic case. The hydrological behavior of the lake under such an assumption was formulated as shown in Eq. 6 and the corresponding plot is shown in Figure 5.

$$F_4 = (f_1 - 0.45) Sin\left[\frac{2\pi}{w}(t - f_3)\right] + f_2 \tag{6}$$

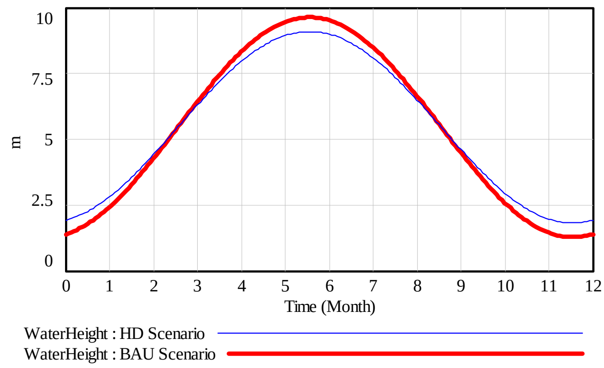

FIG. 5 PROJECTED WATER HEIGHT UNDER (HD) SCENARIO IN COMPARISON WITH BAU SCENARIO.

Eq. 6 is used as a function to test the deterministic system that has been set up to see the behavioral response of P in the lake under the HD scenario. Figure 6 compares the dynamic behavior of P of TS lake for the current and HD scenarios. The simulation results show that for the HD scenario, the P peak concentration of the lake would decrease by about 30% although the basic cyclic behavior does not change significantly.

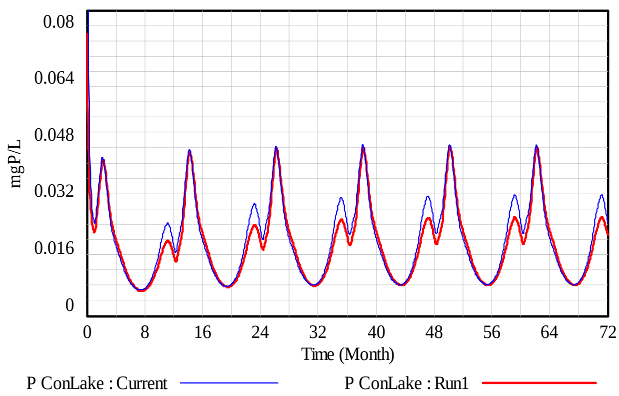

FIG. 6 BEHAVIOR (DETERMINISTIC CASE) OF THE TP UNDER BOTH BAU (CURRENT) AND HD SCENARIOS (RUN1)

Stochastic Case

Stochastic flood magnitude of the lake is expected because there are typically annual variations in rainfall, river stage, wind and weather conditions (Seo and

Canale, 1999). In this section, the stochastic restriction for the variation of the flood magnitude is removed and a stochastic P model was developed for TS lake using the deterministic framework from Eq. 1 and Eq. 2 and Monte Carlo simulation techniques. This stochastic model performed repetitive calculations while randomly changing the values of the maximum water level. Monte Carlo simulations were performed using 1000 random selections from the stochastic distribution of the flood amplitude.

Figure 7 shows the results of Monte Carlo simulation of the P model. The figure shows the 50%, 75%, 95% and 100% confidence bounds for P concentration in the lake in a sample of 1000 simulations. Given certain assumptions made earlier and uniformly varying water level distribution, there is, in month 14, a 50% chance that the lake's P concentration will be between about 0.030 mgP/L and 0.038 mgP/L and 75% chance that P concentration will be between about between 0.029 mgP/L and 0.042 mgP/L and 95% chance that P concentration will be between about 0.027 mgP/L and 0.044 mgP/L and 100% chance that P concentration will be between about 0.026 mgP/L and 0.045 mgP/L.

Simulation results from the stochastic P model showed the significance of the annual variations due to uncertainty in water level. However, the overall behavior of the stochastic model was not significantly different from what generated by the deterministic model. So the P model tends to be relatively robust (Figure 7). It must be clearly noted that the dynamic confidence bounds represent an envelope of values in a sample of simulations and not a particular trajectory (Sterman, 2000). For instance, the lake's P concentration does not follow the path of the lower 95 confidence interval in any of the simulations.

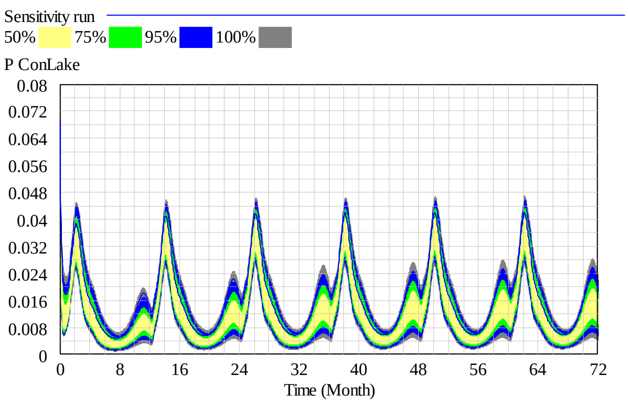

FIG. 7 BEHAVIOR (STOCHASTIC CASE) OF THE TP UNDER STOCHASTIC VARIATIONS OF COEFFICIENTS AND AMPLITUDE OF THE HYDROGRAPH

Conclusion

A relatively simple mass balance model has been shown to be capable of simulating long-term P concentrations in TS Lake. The calculated results are generally in agreement with actual reported concentrations over a one-year period. The parameters of settling rate, regeneration rate and the burial fraction for P were not measured in this study. Rather, model constants were chosen via a calibration approach to agree with actual observations during the period April 2001-April 2002 when actual time-series data is available. Model calibration alone may not be adequate for validation and testing of P model mechanisms (Seo and Canale, 1996). Independent measurements of P fluxes and coefficients should be performed in association with model development to reduce the overall model uncertainty.

Limitations of the model and results can be linked to the modeling process and the data used to calibrate and provide predictions of nutrient conditions. The completely mixed system assumption used in the model in this paper is may be violated in Tonle Sap Lake during the wet season when the lake is deep enough for thermal stratification. This could isolate much of the lake bottom from interactions with the surface layer. Also, there are limitations with the data used in the modeling process. This study assumed nutrient concentrations from the main river channel and tributaries to the TS Lake are the same while this is not known. Similarly, all concentrations of nutrient are from only few sampling locations in the lake.

Despites these drawbacks, the results shown here are encouraging enough to merit further investigation. The model developed and verified in this study appears to work reasonably well for TS Lake. The model is able to handle the interactions between sediments and water satisfactorily. This supports the view that models should consider water-sediment interactions to correctly simulate seasonal or long-term dynamics of P in large shallow lakes similar to TS Lake.

ACKNOWLEDGEMENTS

We are greatly indebted to Matti Kummu, a post-doctoral fellow at the Water and Development Research Group, Aalto University for helpful discussion and the sharing of the data and an anonymous reviewer for comments and suggestions on an earlier version of this manuscript. We are deeply indebted to the financial support for this project

provided in part by the East-West Center, University of Hawaii at Manoa and by the Asia-Pacific Network for Global Change Research (Award #ARCP2012-17NMY-Burnett).

REFERENCES

Beck, M.B. "Hard or soft environmental systems." Ecological Modelling 11 (1981): 233–51.

Boers, P. C., and O.V van Hese. "Phosphorus release from the peaty sediments of the Loosdrecht Lake (Netherlands)." Water Research 22 (1988): 355–63.

Burnett William C. et al. "Using high-resolution in situ radon measurements to determine groundwater discharge at a remote location: Tonle Sap lake, Cambodia." Journal of Radio Analytical and Nuclear Chemistry (2012). DOI 10.1007/s10967-012-1914-8

Campbell, Ian C. et al. "Tonle Sap Lake, the heart of the lower Mekong." In The Mekong: Biophysical Environment of an International River Basin, edited by Ian C. Campbell. Academic Press, 2009.

Campbell, Ian C. et al. " Species diversity and ecology of Tonle Sap Great Lake, Cambodia." Aquatic Science 68 (2006): 355–73.

Carbonnel, P. J., and J. Guiscarfe. Grand Lac du Cambodge: Sedimentologie et Hydrologie 1962–1963. Museum National d'Histoire Naturelle de Paris. Paris, France, 1965.

Chapra Steven C., and Raymond P. Canale. "Long-term phenomenological model of phosphorus and oxygen for stratified Lakes." Water Research 25 (1991): 707-15.

Chapra, Steven C. Surface water-quality modeling. McGraw-Hill, 1997.

Choi, Chang-Hyeon. "Generalizations of the Lotka-Volterra population ecology model: Theory, Simulation, and Applications." Nonlinear Dynamics, Psychology, and Life Sciences 1 (1997): 263-73.

Dillon, P. J., and F. H. Rigler. "A test of a simple nutrient budget model predicting the phosphorus concentration in Lake water." Journal of the Fisheries Research Board of Canada, 31 (1974): 1771-78.

Gartrell, Alexandra. Resource Management in the Cambodian Mekong Basin. Murdoch University, Asia Research Centre, 1997.

Gill, I. Reconciling People and Nature on Cambodia's Tonle Sap. Cambodia: ADB, 2004.

Hand, Taber R. "System structure, natural history, dynamic modeling and adaptive management of the Mekong watershed's Tonle Sap-Great Lake, Cambodia." PhD diss., University of Maryland, 2003.

Imboden D. M. "Phosphorus model of lake eutrophication." Limnology and Oceanography 19 (1974): 297-304.

Ishikawa, Masanobu and Hajime Nishimura. "Mathematical method of phosphate release rate from sediments considering the effect of dissolved oxygen in overlying water." Water Research 23 (1989): 335–51.

Jørgensen, S. E. et al. "Comparison of a simple and complex sediment phosphorus model." Ecological Modelling 16 (1982): 99–124.

Keskinen, Marko. "The Lake with floating villages: A socio-economic analysis of the Tonle Sap Lake." International Journal of Water Resources Development 22 (2006): 463–80.

Keskinen, Marko et al. "The Tonle Sap Lake, Cambodia: Water-related conflicts with abundance of water." The Economics of Peace and Security Journal 2 (2007): 49– 59.

Kite, Geoff. "Modeling the Mekong: hydrological simulation for environmental impact studies." Journal of Hydrology 253 (2001): 1-13.

Kummu, Matti et al. "Sediment: curse or blessing for Tonle Sap lake?" Ambio 37 (2008): 158-163

Kummu, Matti and Juha Sarkkula. "Impact of the Mekong River flow alteration on the Tonle Sap flood pulse." Ambio 37 (2008): 185-92.

Kummu, Matti et al. "Assessing impacts of the Mekong development in the Tonle Sap Lake." Paper presented at International Symposium on Role of Water Sciences in Transboundary River Basin Management. Ubon Ratchathani,Thailand, 2005.

Kummu, Matti and Olli Varis. "Sediment-related impacts due to upstream reservoir trapping, the lower Mekong River." Geomorphology 85 (2007): 275–93.

Lamberts, Dirk. Little impact, much damage: the consequence of Mekong River flow alterations for the Tonle Sap ecosystem. In Modern Myths of the Mekong, edited by Matti Kummu, Marko Keskinen, and Olli Varis. Helsinki University of Technology, 2008.

Lamberts, Dirk and Jorma Koponen. "Flood pulse alterations and productivity of the Tonle Sap ecosystem: A model for impact assessment." Ambio 37 (2008): 178-84.

Lane, Benjamin D. and Bonheur Neou. "Natural resources management for human security in Cambodia's Tonle Sap Biosphere Reserve." Environmental Science and Policy 5 (2002): 33-41.

Lorenzen, M. W. et al. "A long term phosphorus model for Lakes. Application to Lake Washington." In Modeling the Biochemical Processes in Aquatic Ecosystems, edited by Raymond P. Canale, 75-91. Ann Arbor Science Publishers, Michigan, 1976.

Malmaeus, J. M., and L. Håkanson. "Development of a Lake Eutrophication model." Ecological Modelling 171 (2004): 35-63.

Neou, Bonheur. Tonle Sap Ecosystem and Value. Technical Coordination Unit for Tonle Sap. Ministry of Environment, Phnom Penh, Cambodia, 2001.

Rainboth, Walter J. Fishes of the Cambodian Mekong. FAO. Rome, 1996.

Ruley, J. E., and K. A. Rusch. "Development of a simplified phosphorus management model for a shallow, subtropical, urban hypereutrophic Lake." Ecological Engineering 22 (2004): 77-98.

Sarkkula, Juha et al. "Hydropower in the Mekong Region: What are the likely impacts upon fisheries?" In contested waterscapes in the Mekong region-hydropower, lilihoods and govrnance, edited by François Molle, Tira Foran and Mira Kakonen. Earthscan, 2009.

Sarkkula, Juha et al. "Tonle Sap Pulsing System and fisheries productivity." Paper presented at International Congress of Limnology, Lahti, Finland, 2004.

Seo, Dong-il, and Raymond P. Canale. "Analysis of sedimentcharacteristics and total phosphorus models for Shagawa lake." Journal of environmental engineering, 125 (1999): 346-50.

Seo, Dong-il, and Raymond P. Canale. "Performance, reliability and uncertainty of total phosphorus models for lakes—I. Deterministic analyses." Water Research 30 (1996): 83-94.

Scheffer, Marten. Ecology of shallow lake. Kluwer Academic Publicher. The Netherlands, 2004.

Sluiter, Liesbeth. The Mekong Currency: Lives and Times of a River. Utrecht, The Neitherlands, 1993.

Smits, J. and D. van der Molen. "Application of SWITCH, a model for sediment-water exchange of nutrients, to lake Veluewe in the Netherlands." Hydrobiologia 253 (1993): 281-300

Snodgrass, Willam J. and Charles R. O'Melia. "Predictive model for phosphorus in lakes." Environmental Science and Technology 9 (1975): 937-44.

Sterman, J.D. Business dynamics: Systems thinking and modeling for a complex world. McGraw-Hill, 2000.

Van Eck, G. T., and J. G. Smits. "Calculation of nutrient fluxes across the sediment-water interface in shallow Lakes." In Sediments and Water Interactions, edited by P. G. Sly, 289-301. Springer-Verlag, New York, 1986.

Vantana systems, Vensim, Ver. 5. Harvard MA, USA, 2012.

Vollenweider, R. A. "Possibilities and limits of elementary models concerning the budget of substances in Lakes." Archiv für Hydrobiolie 66 (1969): 1–36.

Vollenweider, R. A. A manual on methods for measuring primary production in aquatic environments. Oxford: Blackwell, 1974.

Wang, Hong et al. Adhityan Appan and John S. Gulliver. "Modeling of phosphorus dynamics in aquatic sediments: I—model development." Water Research 37 (2003): 3928-38.

Wang, Shengrui et al. " Phosphorus fractions and its release in the sediments from the shallow lakes in the middle and lower reaches of Yangtze River area in China." Colloids and Surfaces A: Physicochemical and Engineering Aspects 273 (2006): 109-16.